DEVELOPMENT OF MESO-SCALE FLYING ROBOTIC INSECTS

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The creation of a small-scale flying robot is an interesting and complex problem. The problems associated with micro-flight begin with the task of generating lift. This is a difficult aerodynamic problem since classical Bernouli lift is no longer valid for Reynold's numbers below 1000. With small wing areas conventional lift requires high local velocities over the wings to induce lift and reduce skin drag. High velocities are difficult to achieve with small aircraft which becomes the size limiting factor in fixed wing aircraft. However, using biomimetic principles, it is possible to induce lift in the meso and micro-worlds by taking advantage of the once problematic drag in the same manner as insects and some birds. In addition, flapping is a highly efficient way to produce flight. For sustained low energy flight both insects and birds use a complex elastodynamic system which they excite at a natural frequency. This is important due to the limited amount of power an autonomous airborne robot can carry. The actuation device presented is based on these same flight principles used by insects and birds, a resonating elastodynamic system excited at a natural frequency or at some lower harmonic. This allows for long distance flights that require little energy. When coupled with a highly energy dense and non-dissipative actuator, like piezoceramics, the system retains a high efficiency. Piezoceramics possess a high energy level and force output that can excite the device and induce a flapping motion through a set of solid-state kinematic linkages. The solid-state linkages also reduce the amount of losses due to friction in the system by eliminating moving parts such as bearings and gears. The vibratory dynamics of the system rely primarily on the flexure mechanism and the piezoelectric element, but there is also an aerodynamic interaction between the wings and the air, which adds another complex nonlinear problem. The mechanisms used to create flapping motion require precision machining techniques like electric discharge machining, EDM, and micro-machining processes like MEMS and LIGA. With the emergence of MEMS and LIGA technology piezoceramics can be integrated to create tiny solid state devices. The precision motion that piezoelectric materials can provide is complimented by the tolerances that can be achieved through MEMS and LIGA micromachining. The integration of these two technologies is ideal for microactuation as well as the development of flying insects. LIGA based devices as well as conventionally machined mechanisms can be integrated with piezoceramics to mimic the flight mechanics of an insect.

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Classical Aerodynamics

Lift

$F_L = C_L(\rho V^2 S)/2$

- Lift is based on the geometric properties of the wing as well as angle of attack and flow velocity over the wing.
- The above lift equation however is only valid for Reynolds number values above 10^3.
- The lift forces decrease greatly as the Re decreases.

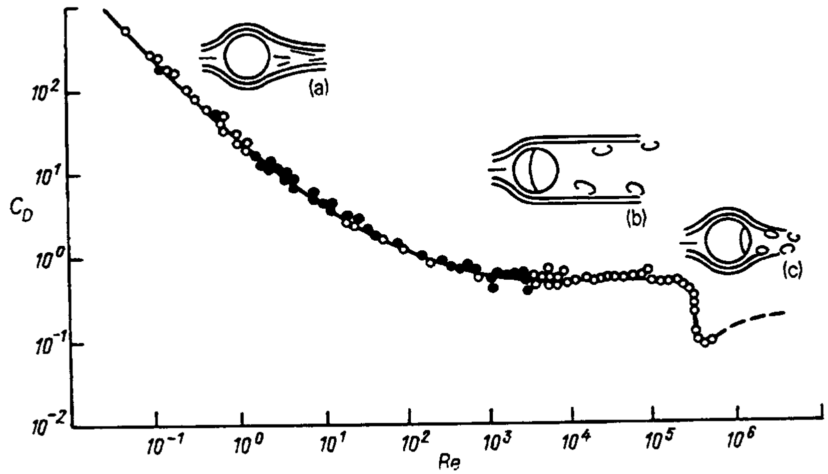
Drag

$F_D = C_D(\rho V^2 S)/2$

- Drag is a function of the projected area of the aircraft perpendicular to the flow and the skin friction of the body and wings.
- The drag equation hold relatively well as the Re decreases.
- This happens because the viscous effects of air become more dominant as the geometry of the object in the flow gets smaller.

Fixed Wing Flight

- Fixed wing aircraft rely on high aspect ratio wings and high Re.
- To keep a high Re small wings have to become stout with low aspect ratios with some as low as 1.
- Since drag increases as the Re decreases small wings on low speed aircraft become inefficient and unable to generate enough lift to keep the aircraft aloft.
- Wings with low Re's act the same as fins in water.
- The graph shows crawling, subcritical, and critical Re flows around a sphere and their drag coefficients.

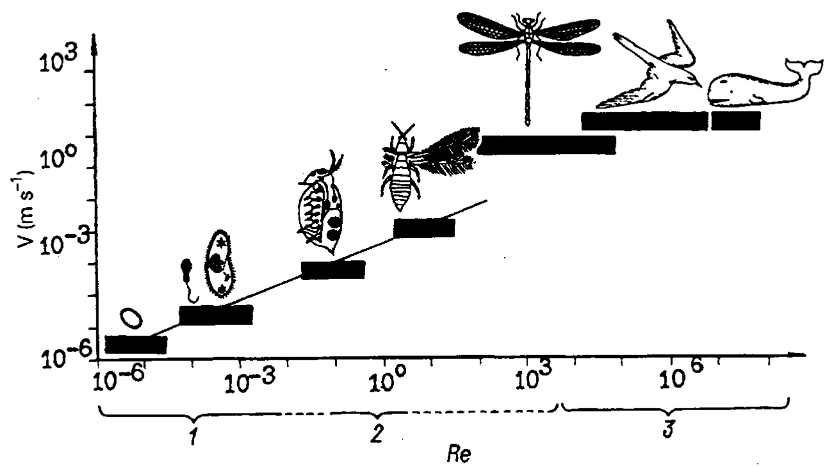


Microscale Aerodynamics

- The Reynolds Number is a ratio of Inertial Forces to Viscous Forces.

$$Re = \rho V l/\mu = V l/\nu$$

- Drag and the relative viscosity of air are problems for classical flight however they are beneficial to insect or flapping flight.
- The basis for microscale flight is the pushing around of air and the increase of the speed of the air across the wing to generate vortices.

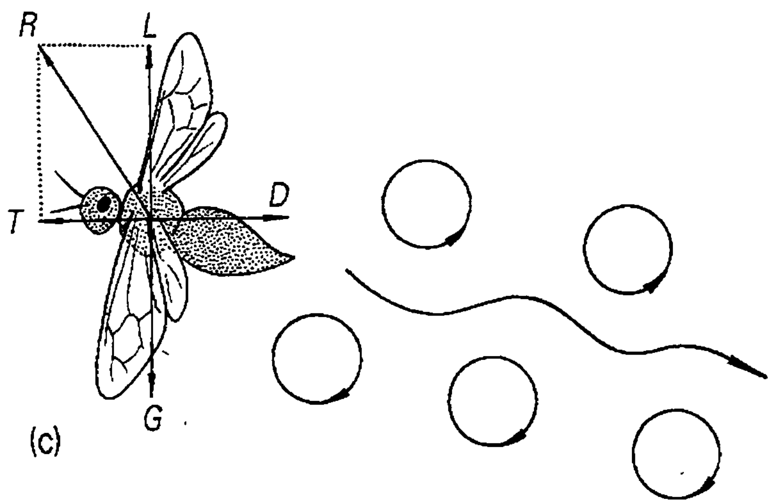


- The first region is strictly dominated by viscous friction.
- The third is dominated by inertial forces.
- The third is a combination of the two effects and is the region of interest.

Flapping Flight

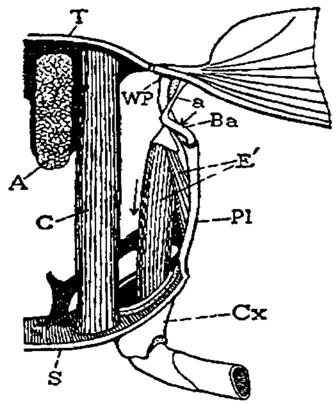
- Flapping uses the viscosity of the air and the drag created by the wing surface to generate lift.
- Classical aerodynamics deal with Re's above 10^3 however the drag force equations still hold as valid approximations for low Re's. (Kubo et.al. 1994)
- Upward thrust can be represented by $T=1/2(\rho A l^2 U^2 S)$ (Brodsky 1994) which closely resembles the equation for drag on a flat plate.

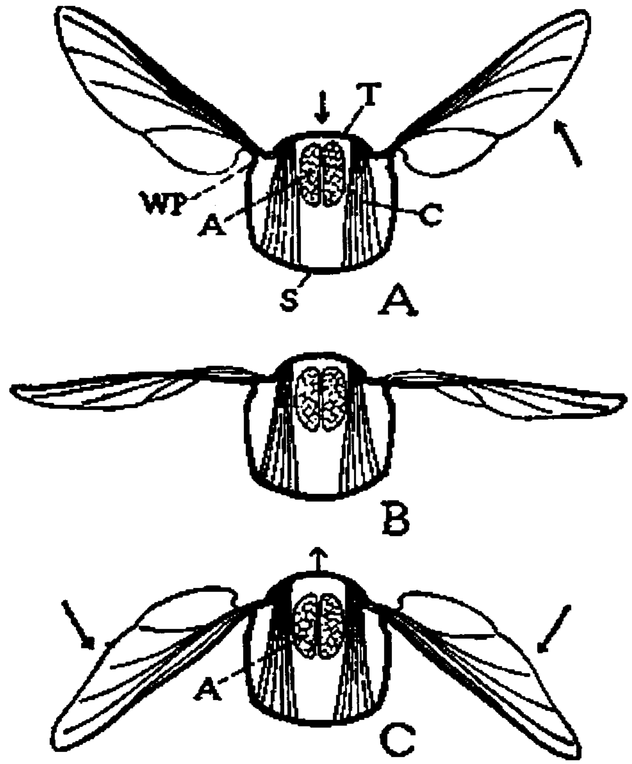
- Flapping a wing creates complex vortices with two major components. (Blackwell and Archer 1986)
  - steady state (creates lift)
  - oscillatory (no net lift)



Insect Anatomy

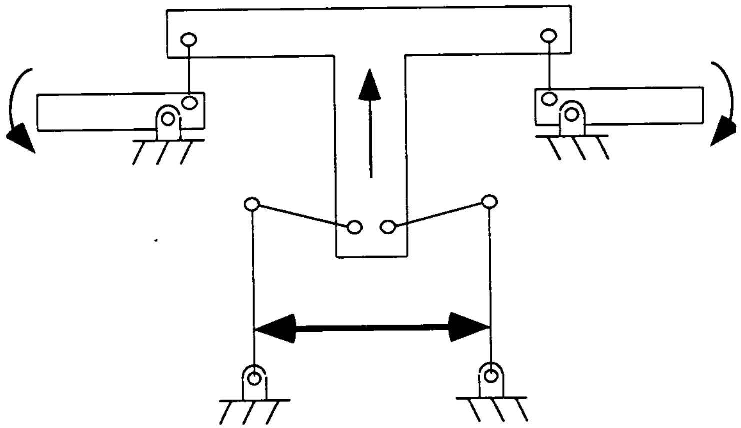
- The internal muscle structure in the thorax deforms the body which in turns causes the wings to flap.
- The wing pivot joints are actually spatial linkages that allow the wing's angle of attack to change throughout each cycle.
- Wings consist of thin membranes and all flying insects have two sets.





Biomimetic Design

- Insects use a complex system of muscles bones and a hard exoskeleton to generate elastodynamic locomotion.
- Insect muscles are rubberband-like structures with low internal damping.
- Insects actuate their muscles at a lower harmonic than the wingbeat frequency. (Alexander 1992)
- A flexure based kinematic mechanism with torsional stiffness at the joints can be used to generate the same motion of an insect's thorax during flight.



– Planar kinematic mechanism that closely mimics the physiology of an insect thorax

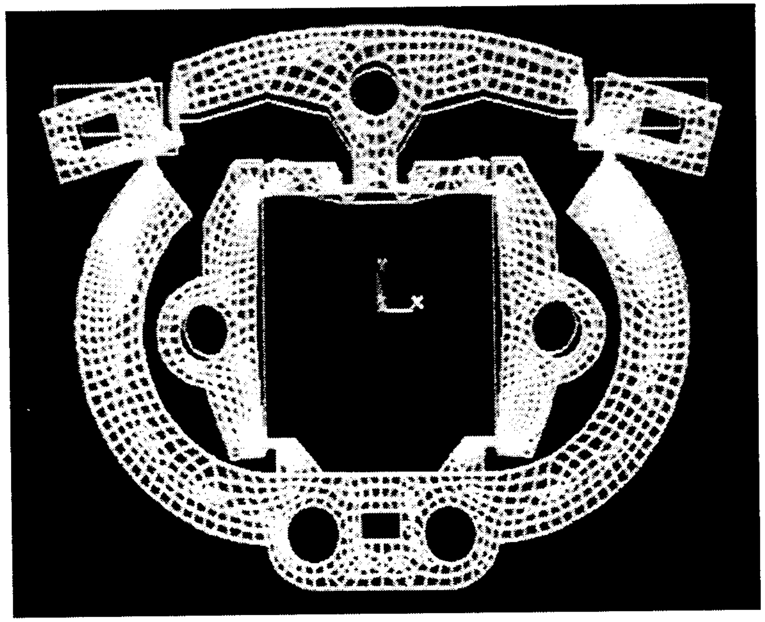
Flexure Mechanism Design

- Metallic structure that imitates the motion of and insect's thorax using the kinematic approximation of a thorax.
- Flexures are used on the microscale since they approximate pivot joints without the mechanical inaccuracies associated with bearings etc.
- Flexures work best in tension so the design incorporates tensile loads on the flexures for the downward "power stroke" and lets the mechanism and drag create the down stroke.

Flapping mechanism is 4mm by 5.5mm

FEM Analysis of the Mechanism

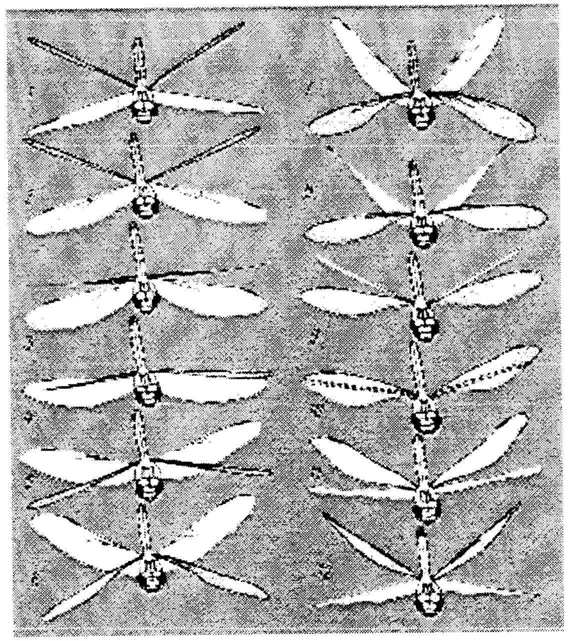
- The first mode is a rocking mode while the second creates the desired flapping motion.
- Fundamental frequencies of the second mode:
  - without wing mass- 586Hz
  - with various wing masses- 14Hz - 20Hz
- The added wing mass decreased the second mode frequency because of the relatively low stiffness of the wing hinges.

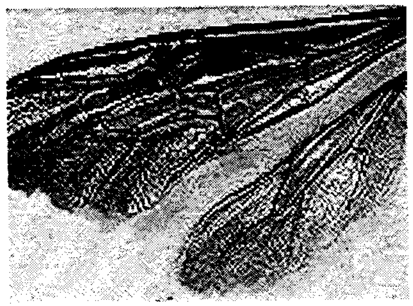


- The second mode is intended to generate a forced flapping motion.

Insect Wing Characteristics

- An insects wings are asymmetric which creates two axes of rotation.
  - One creates the upward and downward strokes.
  - The other changes the wing's angle of attack over the full cycle. (Brodsky, 94)
- Insect wings are textured.
  - The rough surface creates a turbulent boundary layer.
  - This also allows the wing to grip the air.



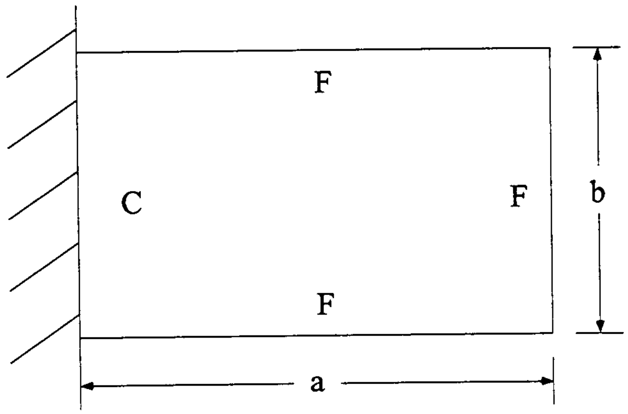


Modeling the Inertial Effects of Air

- Clamped-free-free-free plate model used to approximate an insect wing and its interaction with the air around it. (Blevins, 93)
- Wing mass as well as an added mass due to the inertia of air are used to calculate the first natural frequency.
- The added mass is incorporated into γ which is the mass per unit area.

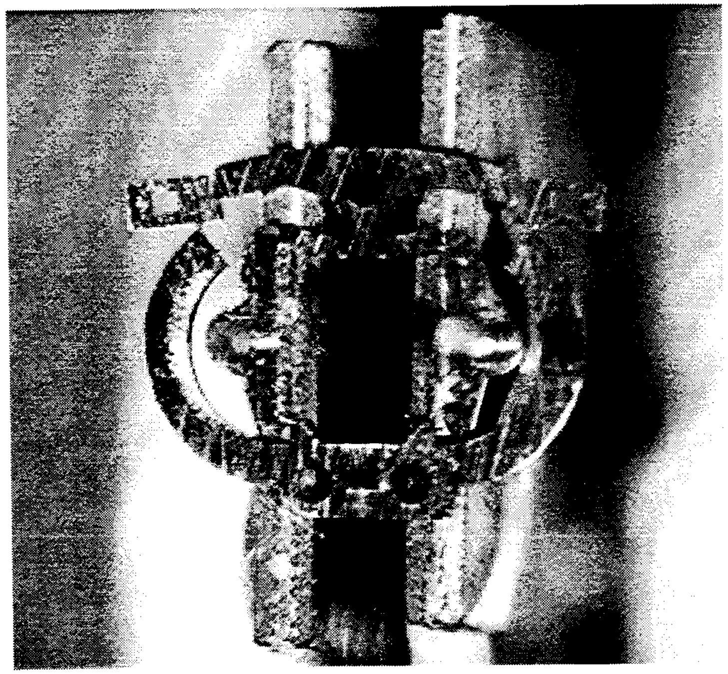
$$2A_p = \frac{\pi}{4}\rho a b^2$$

$$f_{ij} = \frac{\lambda_{ij}^2}{2\pi a^2}\left[\frac{Eh^3}{12\gamma(1-\upsilon^2)}\right]$$



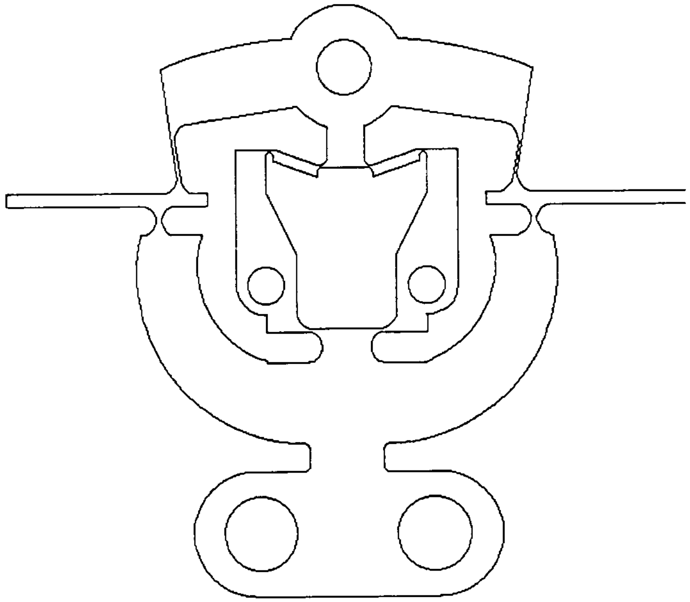
Actuator Integration

- The mechanism is designed to be actuated by some form of piezoelectric material for its high efficiency and energy density.
- Actuator choices are a small monolithic plate or a set of bimorphs (shown).
- The actuator is intended to not only excite the structure but to act as an integral part of the dynamic model.
  - The PZT helps to bring down the resonant frequencies of the system and can be electro-mechanically tuned.
  - The actuator provides stability to the mechanism removing a degree of freedom and the first mode.



Next Generation Design

- EDM mechanism
  - Increased kinematic amplification over previous design
  - Capable of 30° rotational displacement at wing roots given 0.005 inches input
  - Steel and aluminum pieces less ductile than nickel and exhibit better dynamic responses
  - Meso-scale device is better suited for a preliminary wing testing platform



EDM mechanism has a 1.1” wing span

Observations

- Micro aerial vehicles using flapping flight is feasible and the integration of flexure hinge technology with LIGA and MEMS makes the development of robotic insects possible.
- The elastodynamics of the system must be tuned using the mechanical and electrical dynamics of the actuator as well as the wing in order for the entire mechanism's stiffness to be "impedence matched".
- Bimorph actuators are better suited for this application, since they are capable of greater stroke with less parasitic mass, than stack or monolithic elements.

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